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Letter Report

Contaminant Boundary at the Shoal Underground Nuclear Test

prepared by

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Introduction

The U.S. Department of Energy (DOE) has the responsibility to assess the potential health risk to workers and the public from possible exposure to environmental contamination resulting from nuclear testing. The Nevada Division of Environmental Protection (NDEP) is the regulatory agency responsible for preserving the environment of the state to protect public health, sustain healthy ecosystems, and contribute to a vibrant economy. These organizations reached agreement on a corrective action strategy to address the extent and potential impact of radionuclide contamination of groundwater at underground nuclear test locations. This strategy is described in detail in Appendix VI, Section 3, of the Federal Facility Agreement and Consent Order (FFACO, 2000).

As part of the corrective action strategy, the nuclear detonations that occurred underground were identified as geographically distinct corrective action units (CAUs). The objective for each CAU is to estimate over a 1,000-yr time period, with uncertainty quantified, the three-dimensional extent of groundwater contamination that would be considered unsafe for domestic and municipal use. The quantification of the uncertainty is derived from an uncertainty analysis of the groundwater flow and transport model. This report provides the contaminant boundary for the Project Shoal site, CAU447, based on the groundwater flow and transport model for the site (Pohlmann *et al.*, 2004).

Two types of boundaries are discussed in the FFACO that will map three-dimensional groundwater regions, a contaminant boundary and a compliance boundary. Appendix VI of the FFACO (2000) provides the following description of these boundaries:

> A contaminant boundary is the model-predicted perimeter, which defines the extent of radionuclide-contaminated groundwater from underground testing above background conditions exceeding the Safe Drinking Water Act (SDWA) standards. The contaminant boundary will be composed of both a perimeter boundary and a lower hydrostratigraphic unit boundary. The computer model predicts the location of this boundary within 1,000 years and must do so at a 95 percent level of confidence. Additional results showing contaminant concentrations and the location of the contaminant boundary at selected times will also be presented. These times may include the verification period, the end of the five-year proof of concept period, as well as other times that are of specific interest.
>
> From the contaminant boundary predicted by the computer model, a compliance boundary will be negotiated between NDEP and DOE. The compliance boundary will define the area within which the radiological contaminants above the SDWA standards relative to background are to remain. The Department of Energy will be responsible for ensuring compliance with this boundary. The compliance boundary may or may not coincide with the contaminant boundary. If the predicted location of the contaminant boundary cannot be accepted as the compliance boundary, both parties will negotiate an alternate compliance boundary.

The water-quality standard used for determining whether groundwater poses a health risk is specified in the FFACO as the National Primary Drinking Water

Regulations (NPDWRs) for radionuclides, which were developed as a requirement of the Safe Drinking Water Act (regulatory-based boundary). Though not required by the FFACO, DOE also considers the criteria that the U.S. Environmental Protection Agency (EPA) uses in establishing regulatory standards for drinking water contaminants. The EPA target range for lifetime excess cancer risk is not to exceed 10^{-4} and ideally is less than 10^{-6} (EPA, 2000a) (risk-based boundary). This report presents both the regulatory- and risk-based boundary for Project Shoal. The details of the contaminant boundary calculations are given in Pohll *et al.*, 2003.

Groundwater Model

Predictions of radionuclide transport are made using the groundwater flow and transport model of Pohlmann *et al.* (2004). There are two differences between the preliminary transport results in Pohlmann *et al.* (2004) and the results presented in this report. One is the radionuclide mass data. Pohlmann *et al.* (2004) used unclassified source-term data from Hazelton Nuclear Science (1965), while this analysis uses the classified radionuclide mass data. Second, is the manner of presenting the results. Pohlmann *et al.* (2004) present boundaries for the transport of a single radionuclide. The contaminant boundaries presented here combine the transport results for all of the significant radionuclides in the source term, as discussed in detail below.

All transport model calculations are performed using a unit mass value for the starting mass. The unit-mass-based transport analyses are then converted to true mass in a classified environment. This process is performed for six unique classes of radionuclides, which have similar release and retardation characteristics.

The flow and transport simulations are performed in a Monte Carlo environment, which accounts for the parametric uncertainty inherent in all models. The Project Shoal model utilized 1,000 realizations to quantify the uncertainty. Although there are various probabilistic interpretations for how the 95 percent confidence interval of the contaminant boundary can be calculated (see Pohll *et al.*, 2003), this analysis identifies the region where there is 95 percent certainty that contaminants do not pose a health risk rather than identifying with 95 percent certainty the location of contaminants. In other words, the water that does not pose a health risk is external to the region enclosed by the boundary.

Regulatory-based Contaminant Boundary

The regulatory-based contaminant boundary is based on the SDWA standards. This is the metric specified in the FFACO. The regulatory standard is based on three categories of radionuclides:

1. Alpha (α) emitters, excluding uranium
2. Beta (β) and photon emitters
3. Uranium

If one or more of the categorical maximum contaminant levels (MCLs) is exceeded in the groundwater, then the fluid parcel is considered to exceed the regulatory MCL.

For the alpha-emitting radionuclides (*i.e.*, ^{238}Pu and ^{241}Am), the sum of the activity concentrations of alpha-emitting radionuclides is calculated and compared to the

15-pCi/L standard. If the fluid parcel exceeds the 15-pCi/L standard, then the MCL for this fluid parcel is assumed to be violated. Table 1 lists the 28 radionuclides used to calculate the regulatory-based contaminant boundary. Although other radionuclides were identified by Smith (1997), they were not included in this analysis because either the source masses and/or MCLs were not available.

Table 1. List of radionuclides, half lives, MCLs and emission types used to calculate the regulatory-based contaminant boundary.

Isotope	Half life (years)	MCL stand (pCi/L)	Emission type
Tritium	1.23E+01	20,000.0	β
Carbon-14	5.73E+03	2,000.0	β
Chlorine-36	3.01E+05	700.0	β
Nickel-59	7.60E+04	300.0	β
Nickel-63	1.00E+02	50.0	β
Strontium-90	2.91E+01	8.0	β
Zirconium-93	1.50E+06	2,000.0	β
Technetium-99	2.13E+05	900.0	β
Iodine-129	1.57E+07	1.0	β
Cesium-135	2.30E+06	900.0	β
Cesium-137	3.02E+01	200.0	β
Samarium-151	9.00E+01	1,000.0	β
Europium-152	1.35E+01	200.0	β
Europium-154	8.59E+00	60.0	β
Holmium-166m	1.20E+03	90.0	β
Uranium-232	7.00E+01	15.0	U Tox + α
Uranium-233	1.59E+05	15.0	U Tox + α
Uranium-234	2.46E+05	15.0	U Tox + α
Uranium-235	7.04E+08	15.0	U Tox + α
Uranium-236	2.34E+07	15.0	U Tox + α
Uranium-238	4.47E+09	15.0	U Tox + α
Neptunium-237	2.14E+06	15.0	α
Plutonium-238	8.77E+01	15.0	α
Plutonium-239	2.41E+04	15.0	α
Plutonium-240	6.56E+03	15.0	α
Plutonium-241	1.44E+01	300.0	β
Plutonium-242	3.75E+05	15.0	α
Americium-241	4.33E+02	15.0	α

For the β- and photon-emitting radionuclides, such as ^{3}H (tritium), ^{90}Sr, ^{129}I, and ^{137}Cs, a "sum-of-the-fractions" procedure is involved (see EPA, 2000b). First, simulated β- and photon-emitting radionuclides are determined. A conversion table is then created (by procedures described in EPA, 1976), to determine the activity concentration corresponding to an annual dose equivalent of 4 mrem/y for each of the β- and photon-emitting radionuclides for which an activity concentration is predicted. Next, each radionuclide-specific β value (*e.g.*, pCi/L) is divided by the activity concentration (*e.g.*, pCi/L) equivalent to the annual dose equivalent of 4 mrem/y for that particular

radionuclide. This fraction represents the contribution of this radionuclide to the maximum allowable 4-mrem/y limit for all β and photon emitters present. These fractions are then summed for all beta and photon emitters for each fluid parcel (*i.e.*, finite difference cell within the model domain). If the sum exceeds unity, then the location is assumed to exceed the MCL.

For uranium isotopes, the sum of mass concentrations of uranium isotopes (*i.e.*, μg/L) present at each location is calculated. If the sum of mass concentrations exceeds the MCL for uranium (30 μg/L), then the MCL is violated.

The 95 percent regulatory-based boundary is given in Figure 1 (located at the end of this report). The boundary is presented in three different projections (map view, and two cross-sections). Although the radionuclide concentrations were output for numerous time periods, only five (years 2105, 2255, 2505, 2755, 2963) are presented in the contaminant boundary for clarity. The 1,000-year boundary encompasses an area (in map view) of 1.34×10^5 m^2.

Risk-based *Contaminant Boundary*

The risk-based contaminant boundary is based on the morbidity cancer risk. Morbidity cancer risk is the most exhaustive endpoint, as it addresses both fatal and nonfatal cancers. The U.S. Environmental Protection Agency (2000a) identified an excess lifetime cancer risk that does not exceed 10^{-4} and ideally less than 10^{-6} as a reasonable basis for establishing regulatory standards. A limiting lifetime excess cancer morbidity risk of 10^{-6} is presented here to calculate the contaminant boundary at Project Shoal. The boundary for 10^{-4} was also calculated and is not significantly different than that for 10^{-6}.

The risk is calculated as:

$$R(x,t) = \sum_{i=1}^{N} c_i(x,t)(E)(D)(R_i)$$

where $c_i(x,t)$ is the concentration at a position in space (x) and at time (t), E is the ingestion exposure rate, D is the average life duration, and R_i is the radionuclide-specific morbidity cancer-risk coefficient.

The radionuclide activity concentration is derived from the flow and transport simulations and it is assumed that the majority of the uncertainty in the risk calculation is derived from this parameter. The ingestion exposure rate (2 L/day) and average life duration (70 years) are expected values as determined by EPA (1999). The morbidity cancer-risk coefficients are derived by EPA (1999) and are shown in Table 2. Table 2 shows the list of 36 radionuclides used to calculate the risk-based contaminant boundary. Although other radionuclides were identified by Smith (1997), they were not included in this analysis because either the source masses and/or risk coefficients were not available. For instance, risk coefficients are not available for argon-39, krypton-85 and gadolinium-150 and as such, cancer risk cannot be calculated for these radionuclides.

The 95 percent risk-based boundary is given in Figure 2 (located at the end of this report). Again, the boundary is presented in three different projections (map view, and two cross sections), and five time periods (years 2105, 2255, 2505, 2755, 2963). The 1,000-year boundary encompasses an area (in map view) of 2.21×10^5 m^2.

Table 2. List of radionuclides, half lives and risk coefficients used to calculate the risk-based contaminant boundary.

Isotope	Half life (years)	Risk/pCi
Tritium	1.23E+01	5.07E-14
Carbon-14	5.73E+03	1.55E-12
Aluminum-26	7.30E+05	1.73E-11
Chlorine-36	3.01E+05	3.30E-12
Calcium-41	1.03E+05	3.53E-13
Nickel-59	7.60E+04	2.74E-13
Nickel-63	1.00E+02	6.70E-13
Strontium-90	2.91E+01	5.59E-11
Zirconium-93	1.50E+06	1.11E-12
Niobium-94	2.00E+04	7.77E-12
Technetium-99	2.13E+05	2.75E-12
Paladium-107	6.50E+06	2.50E-13
Cadmium-113m	1.41E+01	2.87E-11
Tin-121m	5.50E+01	2.34E-12
Tin-126	1.00E+05	2.56E-11
Iodine-129	1.57E+07	1.48E-10
Cesium-135	2.30E+06	4.74E-12
Cesium-137	3.02E+01	3.04E-11
Samarium-151	9.00E+01	5.55E-13
Europium-150	3.60E+01	4.33E-12
Europium-152	1.35E+01	6.07E-12
Europium-154	8.59E+00	1.03E-11
Holmium-166m	1.20E+03	8.03E-12
Uranium-232	7.00E+01	2.92E-10
Uranium-233	1.59E+05	7.18E-11
Uranium-234	2.46E+05	7.07E-11
Uranium-235	7.04E+08	6.96E-11
Uranium-236	2.34E+07	6.70E-11
Uranium-238	4.47E+09	6.40E-11
Neptunium-237	2.14E+06	6.18E-11
Plutonium-238	8.77E+01	1.31E-10
Plutonium-239	2.41E+04	1.35E-10
Plutonium-240	6.56E+03	1.35E-10
Plutonium-241	1.44E+01	1.76E-12
Plutonium-242	3.75E+05	1.28E-10
Americium-241	4.33E+02	1.04E-10

Compliance Boundary

Following the process outlined in the FFACO, the DOE and NDEP will use the contaminant boundary presented here as a tool in negotiating a compliance boundary for the Shoal underground nuclear test. This will be presented in a Corrective Action Decision Document, which will also report on the results of the corrective action investigations at the site. A Corrective Action Plan will also be produced and will present the plans for validating the groundwater model and monitoring compliance with the negotiated boundary.

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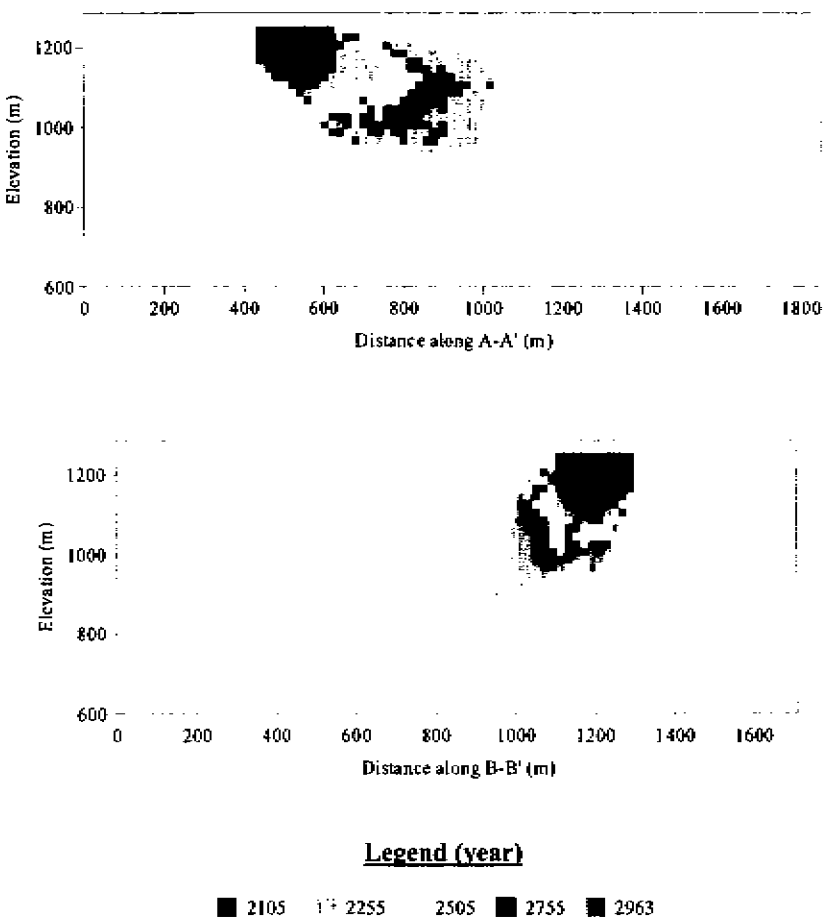
Land Exclusion Boundary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800
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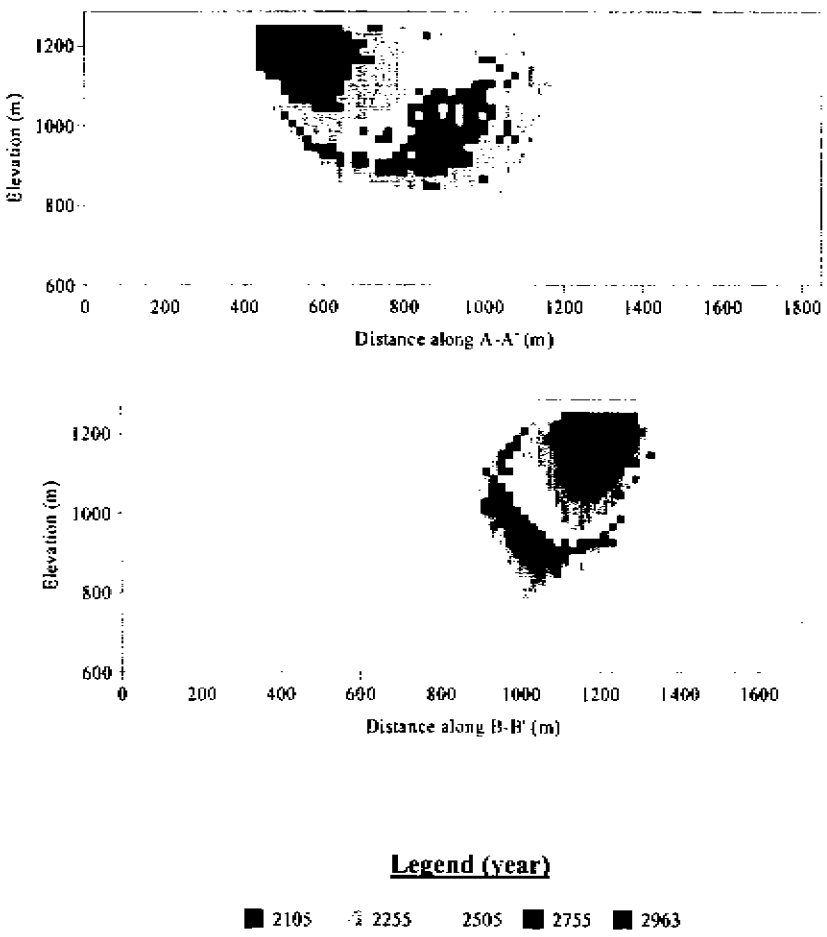
200
400
600
800
1000
1200
1400
1600
1800
Distance along A-A' (m)
Elevation (m)
1200
1000
800
600
0
200
400
600
800
1000
1200
1400
1600
Distance along B-B' (m)
Legend (year)
2105
2255
2505
2755
2963


Land Exclusion Boundary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800
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600
800
1000
1200
1400
1600
1800
Distance along A-A' (m)
Elevation (m)
1200
1000
800
600
0
200
400
600
800
1000
1200
1400
1600
Distance along B-B' (m)
Legend (year)
2105
2255
2505
2755
2963

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